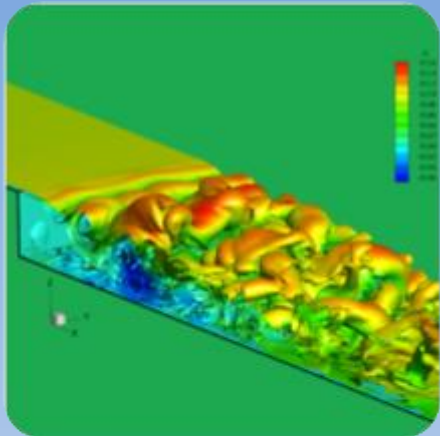
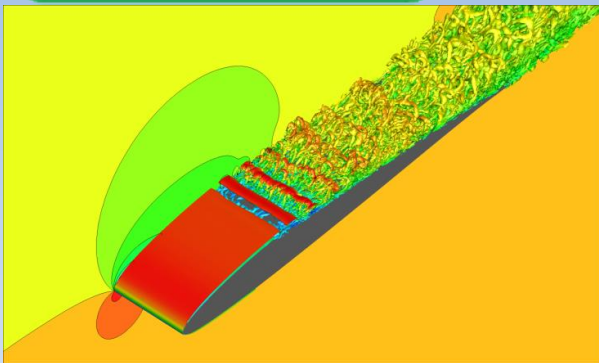


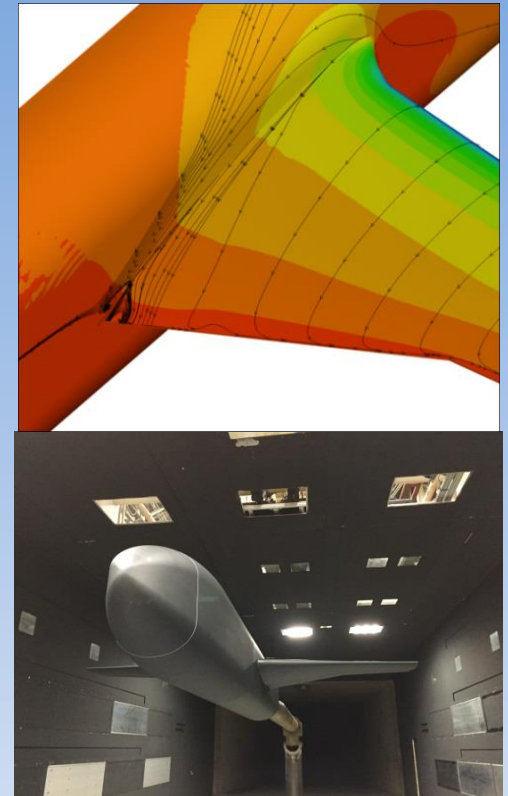
## Revolutionary Computational Aerosciences (RCA)



**Mujeeb R. Malik**  
Technical Lead, RCA  
NASA Langley Research Center  
Hampton, VA



**AIAA SciTech 2016**  
San Diego, CA  
January 4-8, 2016





# Outline

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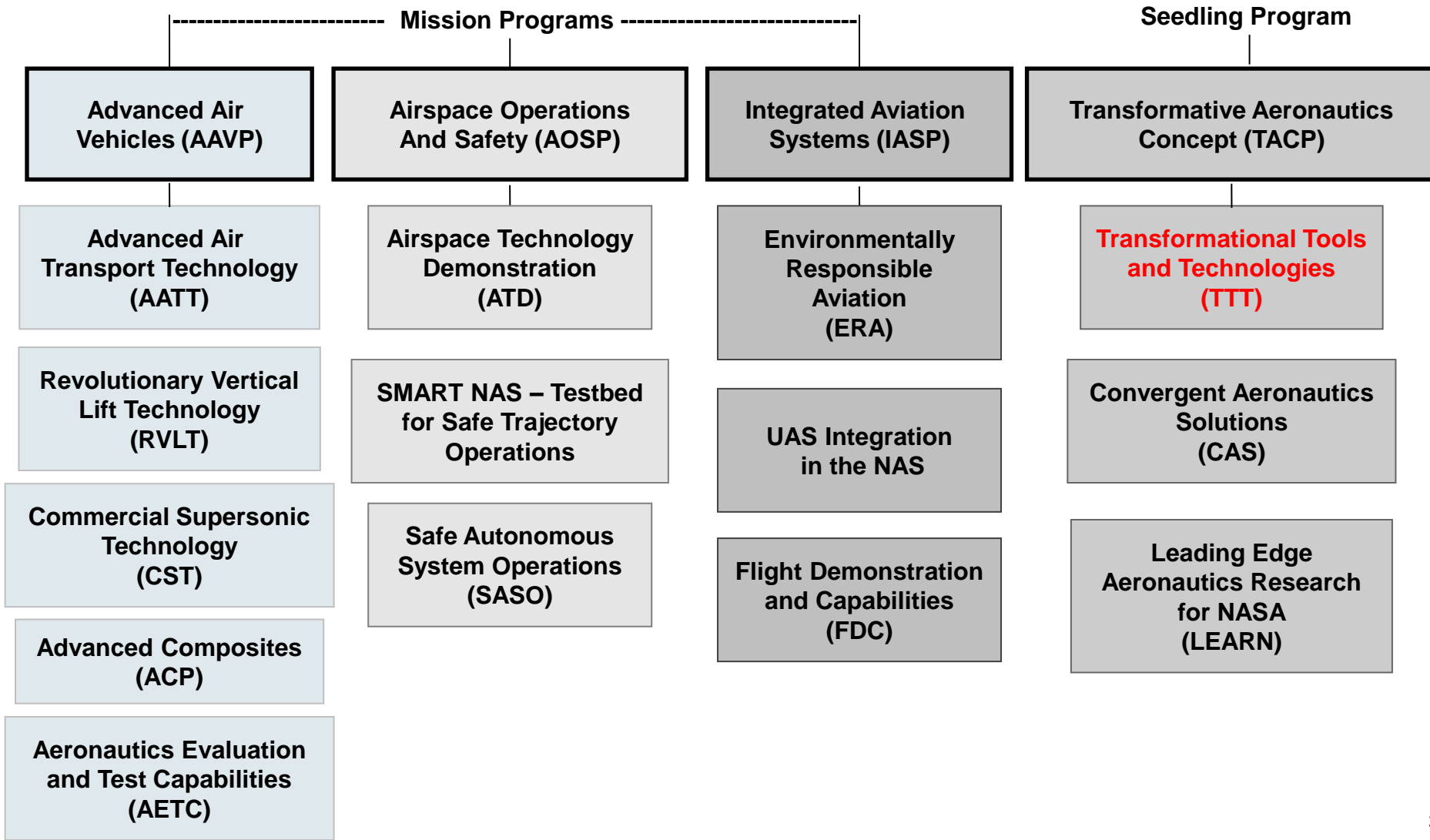
## **Revolutionary Computational Aerosciences (RCA)**

- **Relevance and Vision**
- **Technical Challenge**
- **Research Portfolio**
- **Research Highlights**
- **Summary**

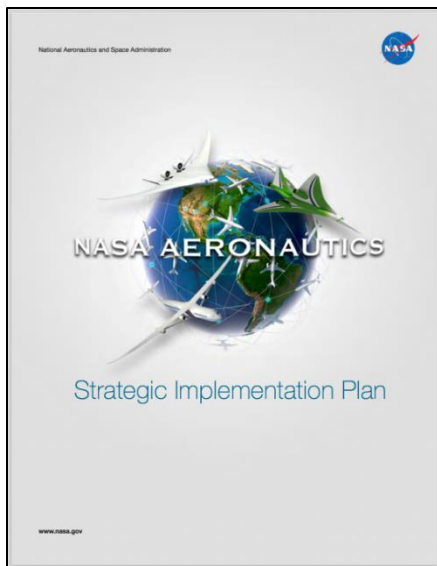


# NASA Aeronautics Program Structure

## Aeronautics Research Mission Directorate



# NASA ARMD SIP and Strategic Thrusts



## Safe, Efficient Growth in Global Operations

- Enable full NextGen and develop technologies to substantially reduce aircraft safety risks



## Innovation in Commercial Supersonic Aircraft

- Achieve a low-boom standard



## Ultra-Efficient Commercial Vehicles

- Pioneer technologies for big leaps in efficiency and environmental performance

Primary  
area of  
RCA  
emphasis



## Transition to Low-Carbon Propulsion

- Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Primary  
areas of  
project  
emphasis



## Real-Time System-Wide Safety Assurance

- Develop an integrated prototype of a real-time safety monitoring and assurance system



## Assured Autonomy for Aviation Transformation

- Develop high impact aviation autonomy applications

T<sup>3</sup> Project develops cross-cutting tools and technologies



# Transformational Tools & Technologies (T<sup>3</sup>)

## Project Management Structure

*Tools for fast, efficient design & analysis of advanced aviation systems & cross-cutting technologies*

PROJECT LEVEL

Executive Team:  
Project Manager – Mike Rogers (Acting, ARC)  
Deputy Project Manager – Rob Scott (LaRC)  
Associate Project Manager – Dale Hopkins (Acting, GRC)

Project - Center Liaisons:  
Mike Rogers (ARC)  
Jeff Bauer (AFRC)  
Laura Stokley (GRC)  
Melinda Cagle (LaRC)

Business Lead – Debra Findley (GRC)  
Center Analysts – Cecelia Town (ARC)  
Lisa Logan (AFRC)  
Joe Sessa (GRC)  
Renee' Williams (LaRC)  
NRA Manager – Renee' Williams (LaRC)  
Scheduler – Joyce Moran (GRC)

SUB-PROJECT

Revolutionary Tools & Methods (RTM)  
SPM – Melinda Cagle (LaRC)  
Sub-Project Technical Leads:  
RCA – Mujeeb Malik (LaRC)  
Combustion Modeling – Jeff Moder (GRC)  
MDAO/SA – Jeff Viken (LaRC)  
M&S Modeling – Dale Hopkins (GRC)

Development of revolutionary comprehensive physics-based aeronautics analysis and design capability.  
Philosophically based on Vision 2030 study recommendations.  
Current Technical Challenge to reduce CFD error by 40% by 2017.

Critical Aeronautics Technologies (CAT)  
SPM – Laura Stokley (GRC)  
Sub-Project Technical Leads:  
M&S Technologies – Dale Hopkins (GRC)  
iMeasurements – Tom Jones (LaRC)  
Propulsion Controls – Dennis Culley (GRC)  
Flight Controls – Jay Brandon (LaRC) and Joe Pahle (AFRC)  
Combustion Technologies – Jeff Moder (GRC)

Development of critical aeronautics technologies that can enable revolutionary improvement in aircraft system design. Innovative ideas that may lead to patentable results.  
Current Technical Challenge to develop 2700F-capable engine materials by 2017.



# CFD Vision 2030 Study



- NASA commissioned a one-year study to develop a **comprehensive and enduring vision** of future CFD technology:
  - HPC
  - Physical Modeling
  - Numerical Algorithms
  - Geometry and Grid Generation
  - Multidisciplinary Analysis and Optimization
- **Wide community support for the research roadmap:**
  - Aerospace America, Aviation Week & Space Technology
  - AIAA Aviation 2014 Panel Discussion
  - Independent Activities/Forums

**NASA CR 2014-218178**



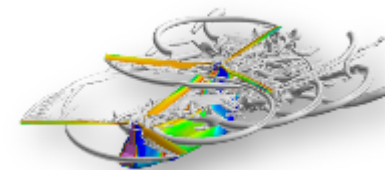
Report (published March 2014) available at:  
<http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140003093.pdf>



# Vision of CFD in 2030

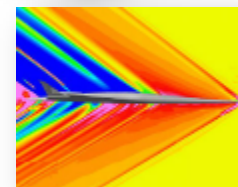
## Emphasis on physics-based, predictive modeling

- Transition, turbulence, separation, chemically-reacting flows, radiation, heat transfer, and constitutive models, among others.



## Management of errors and uncertainties

- From physical modeling, mesh, natural variability, lack of knowledge in the parameters of a particular fluid flow problem, etc.



## A much higher degree of automation in all steps of the analysis process

- Geometry creation, meshing, large databases of simulation results, extraction and understanding of the vast amounts of information generated with minimal user intervention.



## Ability to effectively utilize massively parallel HPC architectures that will be available in the 2030 time frame

- Capacity- and capability-computing tasks in both industrial and research environments.



## Seamless integration with multi-disciplinary analyses

- High fidelity CFD tools, interfaces, coupling approaches, etc.



Predictive and automated physics-based tools required for timely analysis/design of novel configurations.

- Represent critical **step changes** in engineering design capability
- May **not** be routinely achievable by 2030
- Representative of key elements of major NASA missions (**ARMD, HEOMD and STMD**)



1. Large Eddy Simulation (LES) of a powered aircraft configuration across the full flight envelope
2. Off-design turbofan engine transient simulation
3. Multi-Disciplinary Analysis and Optimization (MDAO) of a highly-flexible advanced aircraft configuration
4. Probabilistic analysis of a powered space access configuration







# Technology Development Roadmap

TRL ■ LOW  
■ MEDIUM  
■ HIGH

◇ Technology Milestone

★ Technology Demonstration

⊕ Decision Gate

2015

2020

2025

2030

## HPC

CFD on Massively Parallel Systems

**PETASCALE**

Demonstrate implementation of CFD algorithms for extreme parallelism in NASA CFD codes (e.g., FUN3D)

Demonstrate efficiently scaled CFD simulation capability on an exascale system

30 exaFLOPS, unsteady, maneuvering flight, full engine simulation (with combustion)

CFD on Revolutionary Systems (Quantum, Bio, etc.)

**PETASCALE**

Demonstrate solution of a representative model problem

NO

YES

NO

YES

**EXASCALE**

## Physical Modeling

Improved RST models in CFD codes

Highly accurate RST models for flow separation

**RANS**

**Hybrid RANS/LES**

**LES**

**Combustion**

Integrated transition prediction

Chemical kinetics calculation speedup

Unsteady, complex geometry, separated flow at flight Reynolds number (e.g., high lift)

WMLES/WRLES for complex 3D flows at appropriate Re

Unsteady, 3D geometry, separated flow (e.g., rotating turbomachinery with reactions)

## Algorithms

**Convergence/Robustness**

**Uncertainty Quantification (UQ)**

**Fixed Grid**

**Adaptive Grid**

Automated robust solvers

Reliable error estimates in CFD codes

Tighter CAD coupling

Production AMR in CFD codes

Grid convergence for a complete configuration

Scalable optimal solvers

Large scale parallel mesh generation

Large scale stochastic capabilities in CFD

## Geometry and Grid Generation

## Knowledge Extraction

**Integrated Databases**

**Visualization**

Simplified data representation

Creation of real-time multi-fidelity database: 1000 unsteady CFD simulations plus test data with complete UQ of all data sources

On demand analysis/visualization of a 100B point unsteady CFD simulation

On demand analysis/visualization of a 100B point unsteady CFD simulation

## MDAO

Define standard for coupling to other disciplines

High fidelity coupling techniques/frameworks

Incorporation of UQ for MDAO

Robust CFD for complex MDAs

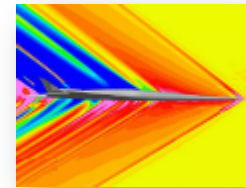
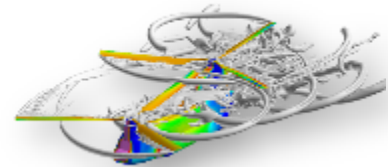
MDAO simulation of an entire aircraft (e.g., aero-acoustics)

UQ-Enabled MDAO

# The Way Forward

- **Study recommendations requiring additional investment:**

- Access to HPC for “capability” computing
- Validation experiments
  - Juncture Flow, THX, NRA: separation, compressible free shear layer
- Collaborations with academia/research institutes
  - 17 new NRA awards in Vision 2030 areas of RCA, MDAO, and Combustion (including mesh generation)
- Solution adaptive grids (human out of the loop)
- High-fidelity multidisciplinary analysis and design optimization
  - NRA awarded
- Software development infrastructure/frameworks



- **Collaborations will aim to solve Grand Challenge Problems**

- NRA evaluating wall-modeled LES of realistic configurations
- Suggested by the CFD Vision 2030 Study
- Others chosen in consultation with ARMD projects
- Opportunity for “Centennial Challenge”-like awards



# Revolutionary Computational Aerosciences

## Technical Challenge

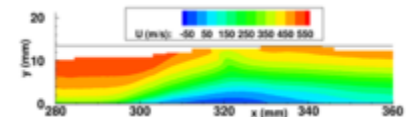
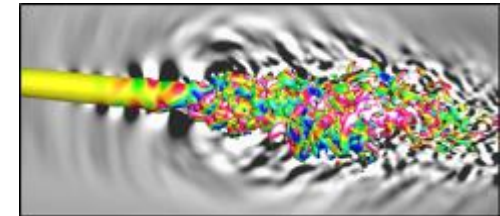
Identify and downselect critical turbulence, transition, and numerical method technologies for 40% reduction in predictive error against standard test cases for turbulent separated flows, evolution of free shear flows and shock-boundary layer interactions on state-of-the-art high performance computing hardware.

## Technical Areas and Approaches

- Development of more accurate physics-based methods (e.g. higher moment closure, large eddy simulation (LES))
- Advanced numerical methods
- Transition prediction and modeling
- Validation experiments
- Multidisciplinary analysis and design (high fidelity)

## Benefit/Pay-off

- Capability will be used by the aeronautics community to improve designs and reduce design cycle times.
- Facilitates accelerated introduction of advanced air vehicles and propulsion systems into the airspace system.
- Supports ARMD Strategic Thrusts # 2, 3 and 4.

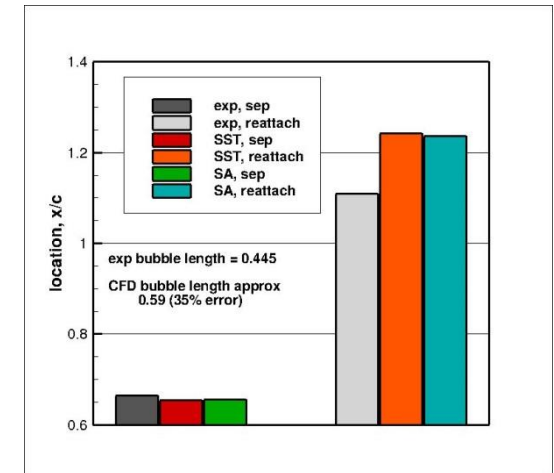


Technical Challenge: Physics-Based Turbulence Models & Simulations

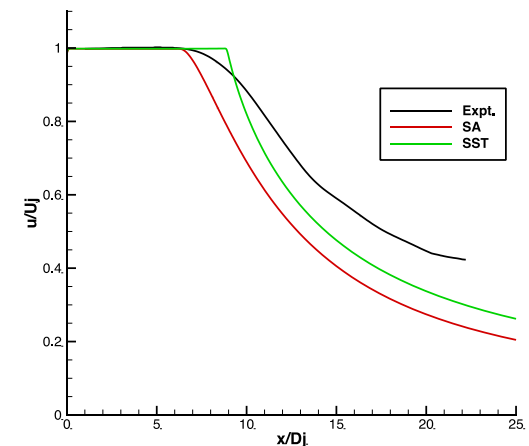


- **NASA Centers: Ames, Glenn and Langley**
  - Computational and Experimental Research
- **Industrial/Other Government Stake Holders**
  - Technical Interchange Meetings to discuss technical areas of mutual interest
- **Engage Academia via NRAs**
  - 12 NRAs completed
  - 8 New awarded
    - 3 Turbulence simulations
    - 2 Numerical Methods
    - 1 Parallel Mesh Generation
    - 2 Validation Experiments

- RCA TC Requires 40% error reduction in turbulent flow predictions
- Define “standard” test cases to enable quantification of prediction improvement
- **Primary test cases**
  - NASA 2D hump
  - Axisymmetric transonic bump
  - 2D shear layer
  - Axisymmetric jet
  - Axisymmetric compression corner
- **Secondary test cases**
  - ONERA M6
  - FAITH
  - NACA 4412 at AoA
  - 2-D Wake Flow
  - ---
- **New CFD Validation Experiments**



**Separation and Reattachment Locations for NASA 2D Hump**



**Centerline Velocity Profiles for NASA M=0.9 Cold Jet**

- **Full Reynolds Stress Models Implemented in NASA CFD Code, FUN3D**

- 7 equations vs. 1 or 2 equations
  - DLR's SSG/LRR-RSM-w2012
  - WilcoxRSM-w2006

- **No improvement in prediction of flow separation over simpler (SA/SST) models**

- NASA Wall-mounted Hump,
- Axis-symmetric Transonic Bump (not shown)
- ONERA M6

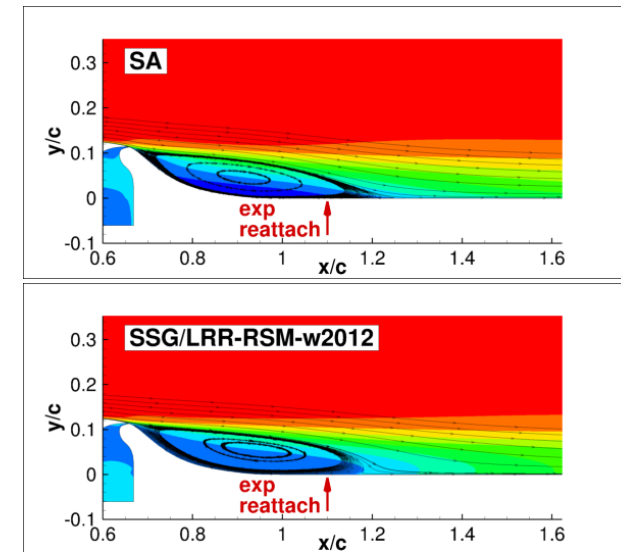
- **Some evidence that corner flow separation will be better predicted**

- Juncture flow experiment will provide data to test out the hypothesis

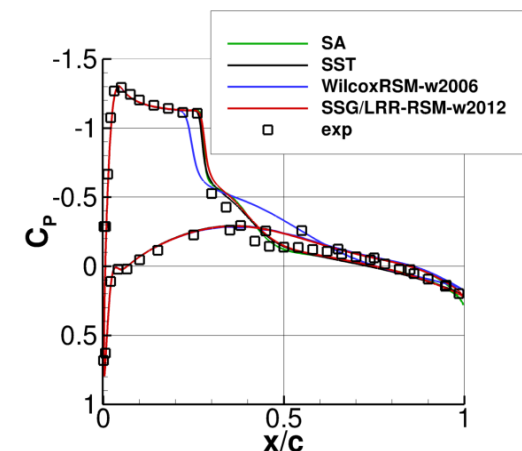
- **Research needed to strengthen weak links**

- Pressure/strain correlation
- Length scale equation

ONERA M6 pressure coefficient at 90% span station;  $\alpha=4.08$  deg case

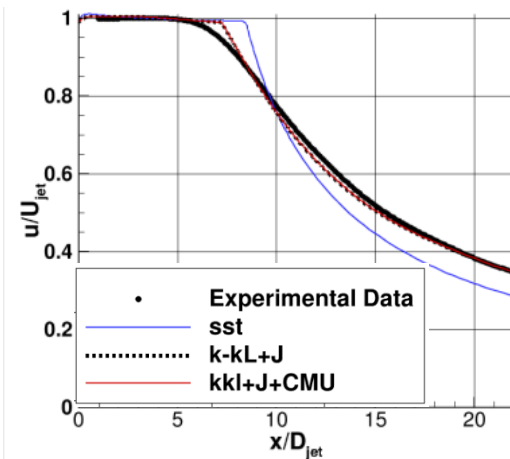


Results for NASA wall-mounted hump

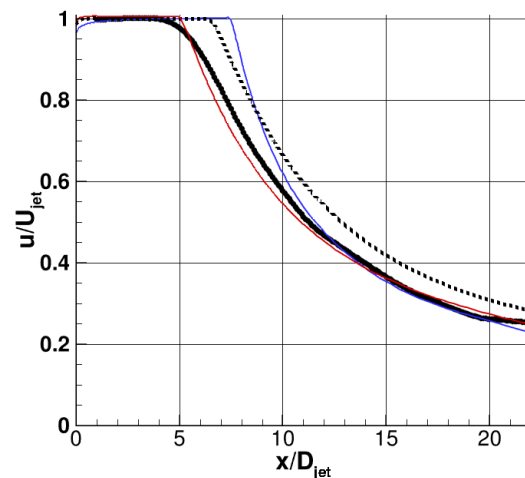




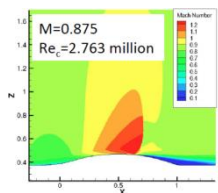
- Length scale equation the weakest link in 2-equation turbulence modeling
  - Menter's modification to Rotta's two equation (K-kL) model
  - Abdol-Hamid's improvement of Menter's model
    - K-kL-MEAH2015 implemented in FUN3D (NASA/TM-2015-218968)
    - Additional modifications for jet flow (K-kL+J) and temperature effects (K-kL+J+Mu)
- Much improved flow predictions
  - Axisymmetric Transonic Bump
    - Error in separation length reduced from 28% (SST) to 8%
  - Cold and Hot Jets
    - Significant improvement in CL velocity prediction



Comparisons of turbulence models results for **cold** subsonic jet (Bridge's M=0.5; sp3)



Comparisons of turbulence models results for **hot** subsonic jet (Bridge's M=0.376; sp23)

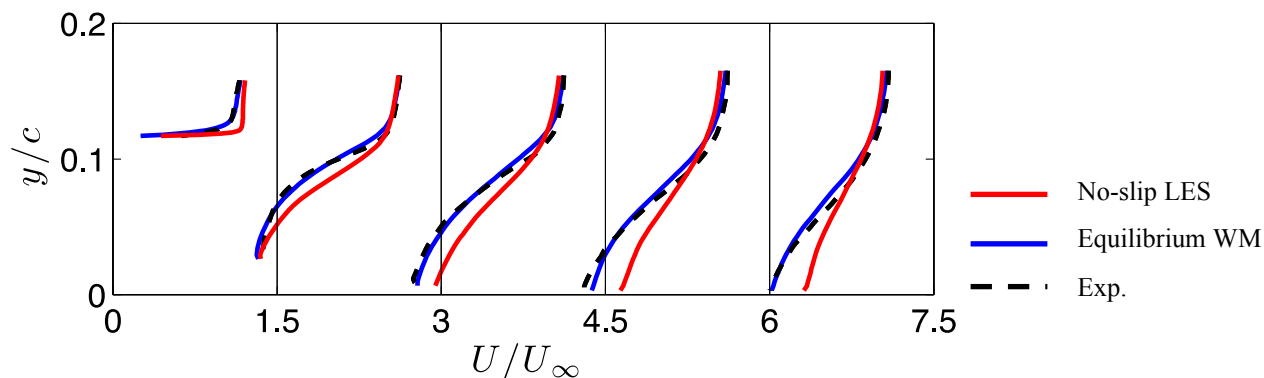


Prediction of Flow Separation for Transonic Bump

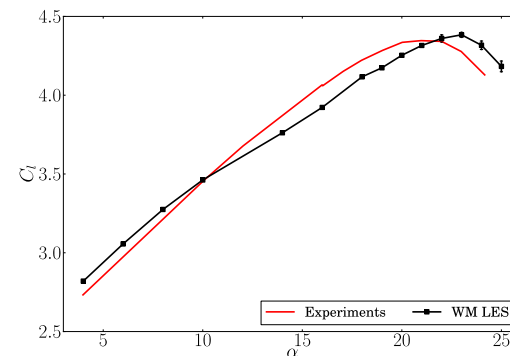
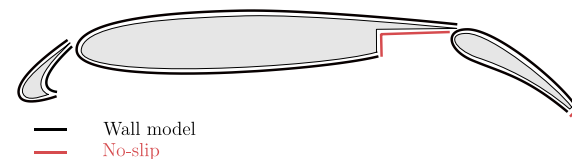
Data	Experiment	K-kL	SST
Separation Location	0.70	0.68	0.65
Reattachment Location	1.10	1.11	1.16
Bubble Size Error (%)		7.50	27.5

# Large Eddy Simulation (LES)

- Two of the Grand Challenge Problems Require Use of LES
- The challenge is How to Reduce Cost?
  - Wall-modeled LES
  - Hybrid RANS/LES Approach
  - Speedup by using advanced numerical methods
- Recent/ongoing/future LES efforts
  - High-Lift Configuration (30P/30N)
  - RCA standard test cases
  - Common Research Model
    - A first step towards GC Problem #1



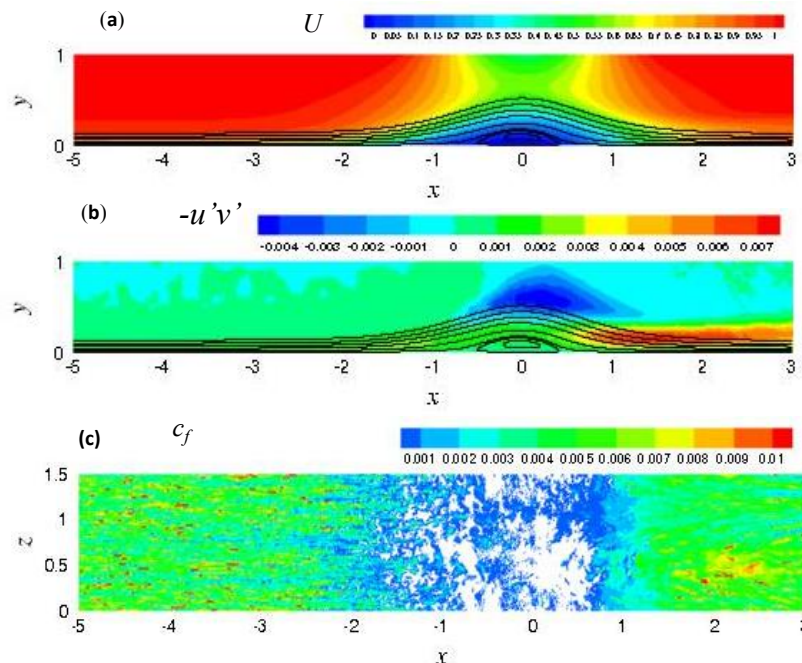
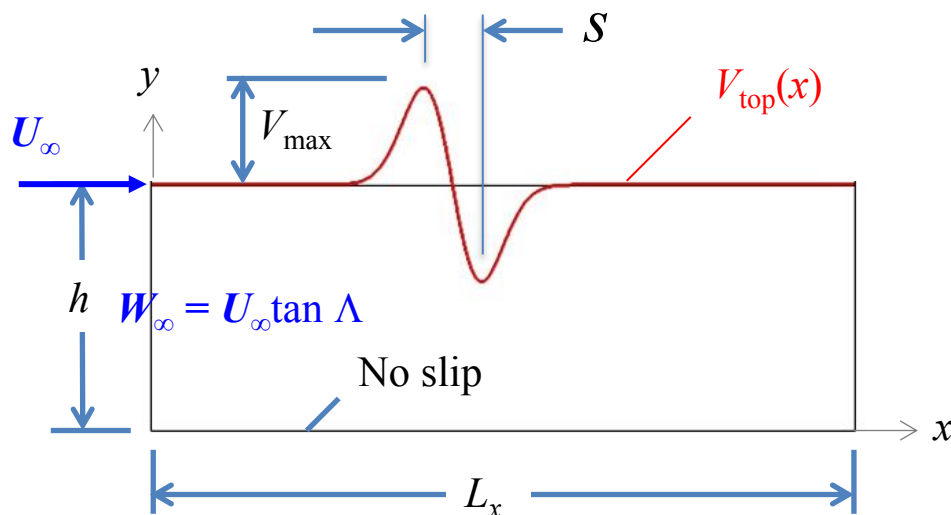
NASA Hump: Flow reattaches at  $X/C = 1.1$  in experiment and WMLES



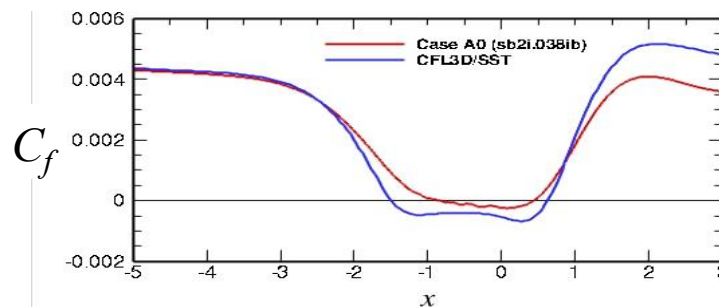
WMLES of 30P/30N

# DNS of Turbulent Smooth-wall Separation

- **Produce high-fidelity data for smooth-wall separation**
  - Use it to diagnose limitation of RANS and hybrid RANS/LES methods
  - Improve RANS models
- **Example DNS currently underway**
  - Coleman, Spalart, Rumsey
  - Fully spectral method with 2 billion points
  - Induce separation on a flat plate by imposing a transpiration velocity profile at the top boundary adverse pressure gradient on a flat-plate
  - With and without sweep



DNS of separation and reattachment in a turbulent boundary layer: (a) Mean streamwise velocity  $U$ ; (b); Reynolds shear stress  $-<u'v'>$ ; (c) instantaneous skin friction.  $Re=40000$ .



Skin friction using RANS and DNS.

# CFD Validation Experiments - 1

## • Juncture Flow Experiment

- Prediction of trailing edge corner separation a challenge
- Risk reduction experiments to develop final design

## • Shock wave/Boundary Layer Interaction

- Mach 2.5 Axisymmetric SWBLI (attached and separated)
- Mean and turbulent stress data

## • Turbulent Heat Flux

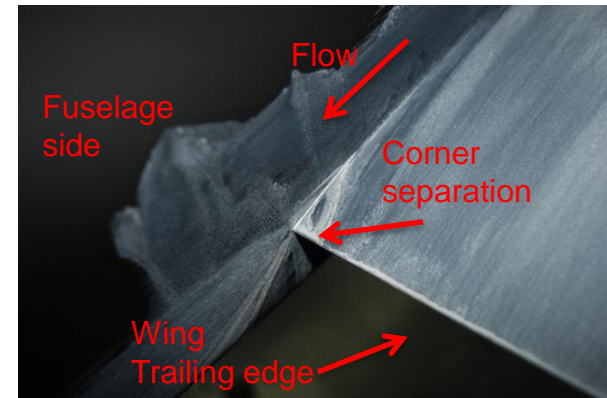
- Multi-hole film cooling (advanced nozzles and turbines)
- Mean and turbulent stress data

## • 2D Separation

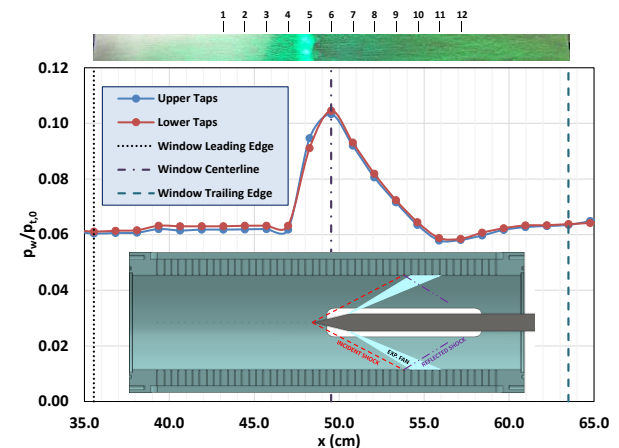
- NRA to Notre Dame (Flint and Corke)
- Data for attached and separated (incipient, small, large) flow

## • 2D Mixing Layer

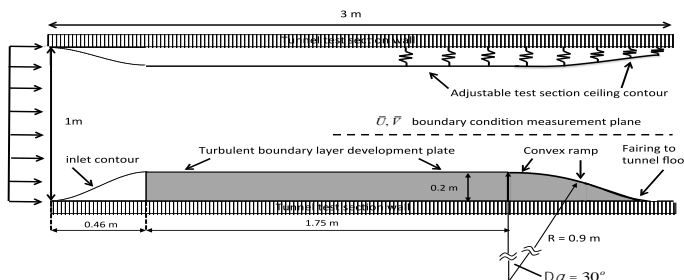
- NRA to U-Illinois (Dutton and Elliott)
- Full documentation of BC and mean/turbulence data



Experimental surface flow visualization



Axisymmetric SWBLI – 13.5° Cone Angle



Notre Dame Model

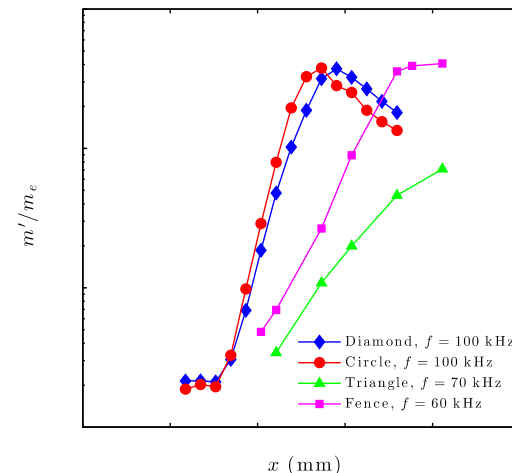
# CFD Validation Experiments - 2

## • Supersonic Boundary-Layer Transition

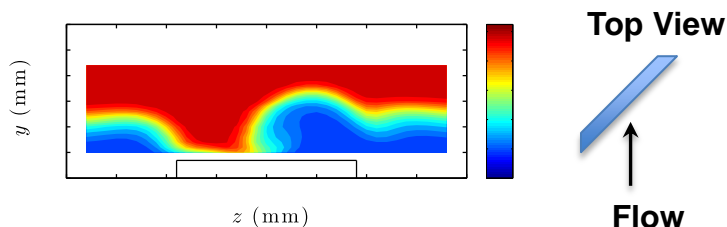
- Mach 3.5 quiet tunnel
- Effect of discrete roughness
  - Qualitative and quantitative agreement between experiment and computation
- Effect of distributed roughness

## • Subsonic Boundary-Layer Transition

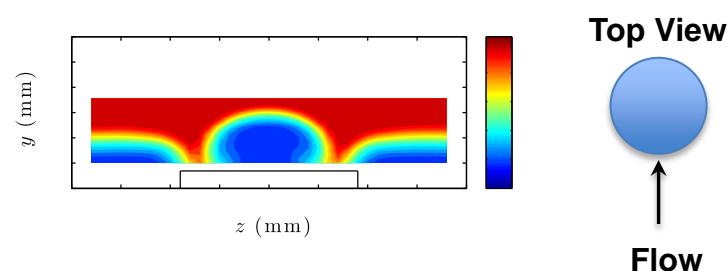
- Effect of surface steps on transition
  - Important for laminar flow wings
- Effect of distributed roughness on transition



Effect of roughness planform shape on the disturbance growth and peak frequency



Mean mass-flux in the wake of the 45-degree fence roughness element



Mean mass-flux in the wake of the circular roughness element

# Holistic Transition Prediction

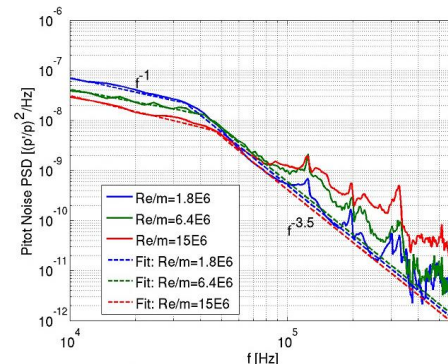
- **Transition an Initial Boundary Value Problem**
  - External Forcing (roughness, acoustic, turbulence, ...)

- **Require A Holistic Approach for Transition Prediction**

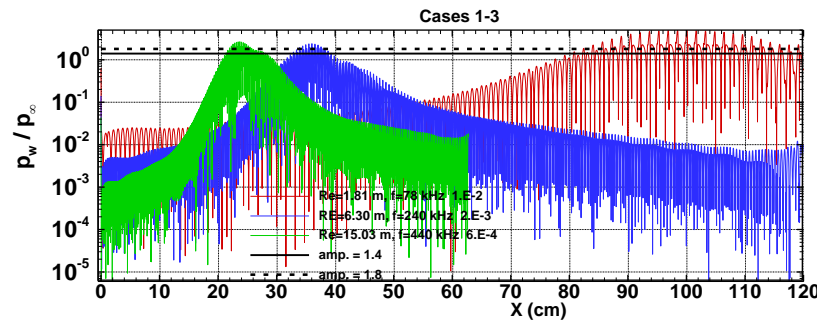
- Use measured free stream disturbance spectra (amplitude/frequency) as BC
- DNS (NPSE) of boundary layer disturbance evolution
- Threshold disturbance amplitude  $((p_{amp})_T)$  as indicator for transition

- **Results [Example]**

- Transition in AEDC Hypervelocity Wind:
  - Mach 10
  - 7 – degree cone
  - Nose bluntness,  $R_n = 0.152, 5.08 \text{ mm}$
  - Different unit Reynolds numbers
- Amplitude based approach provides good prediction of transition
  - N factor does not, as free stream forcing varies



Freestream PSD in the AEDC Tunnel 9.



Amplitude of the pressure fluctuations on the wall generated by the slow acoustic waves.

Predicted and measured transition onset points.

Case	X <sub>T</sub> (cm)			N		
	(p <sub>amp</sub> ) <sub>T</sub>		Expt.	(p <sub>amp</sub> ) <sub>T</sub>		PSE
	1.4	1.8		1.4	1.8	
1	81	84	84	3.2	3.6	4.1
2	33	34	36	5.3	5.7	5.1
3	22	23	25	6.5	6.9	7.0



- **High-Order Schemes for Unsteady Flow Simulations**

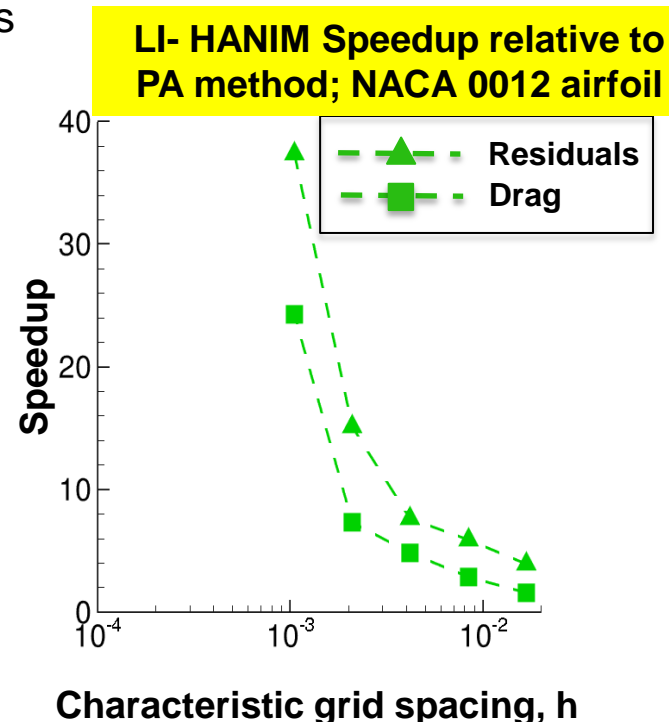
- Entropy Stable Spectral Element Framework
- Space-Time Discontinuous Galerkin Scheme
- Space-Time Conservation-Element/Solution-Element (CESE) Scheme
- Flux Reconstruction (FR) Scheme
  - Subject of next 4 presentations

- **Convergence Acceleration**

- Hierarchical Adaptive Nonlinear Iteration Method (HANIM)
- 2 to 20 times speed up for various test cases

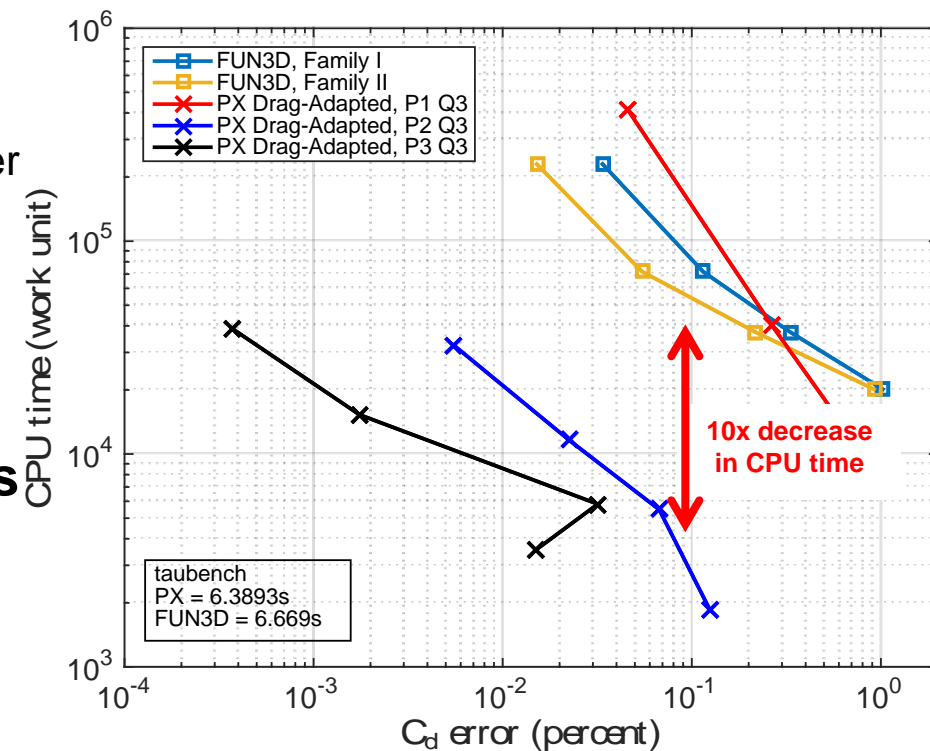
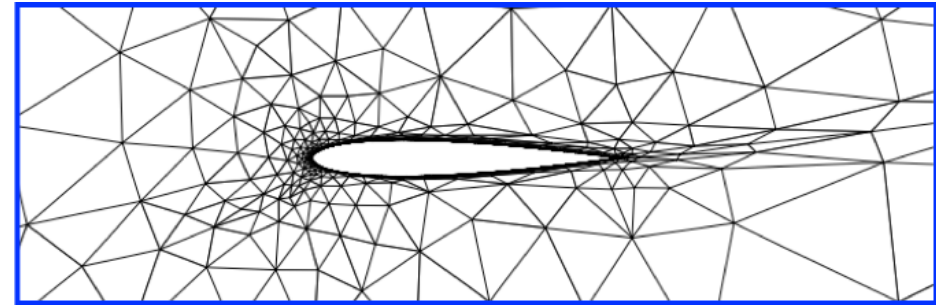
- **Grid Adaptation**

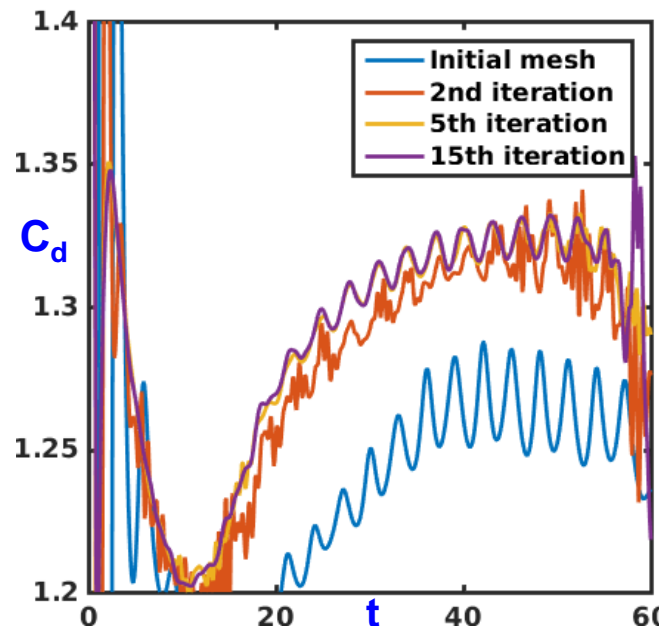
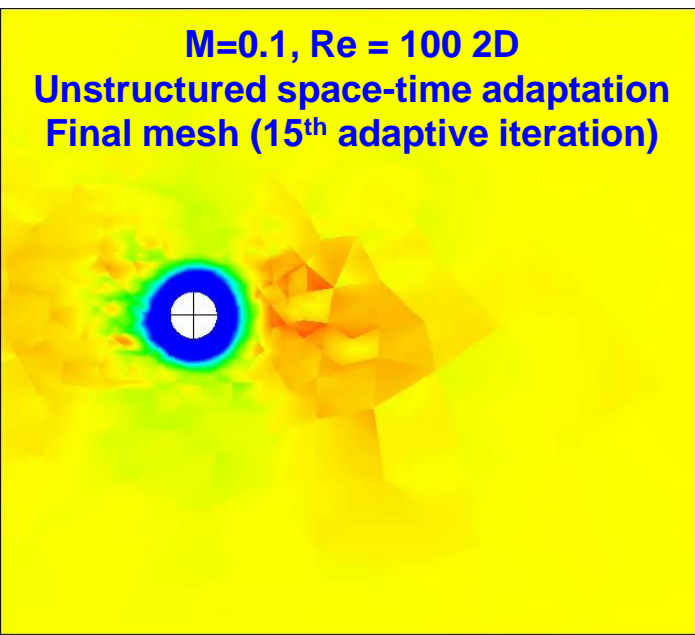
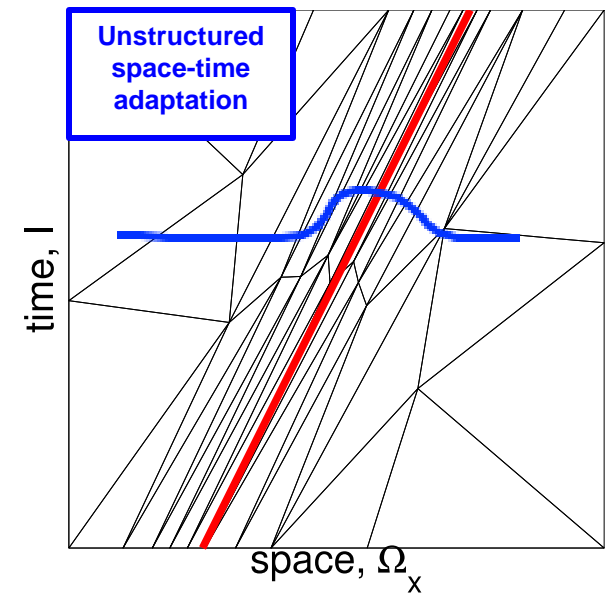
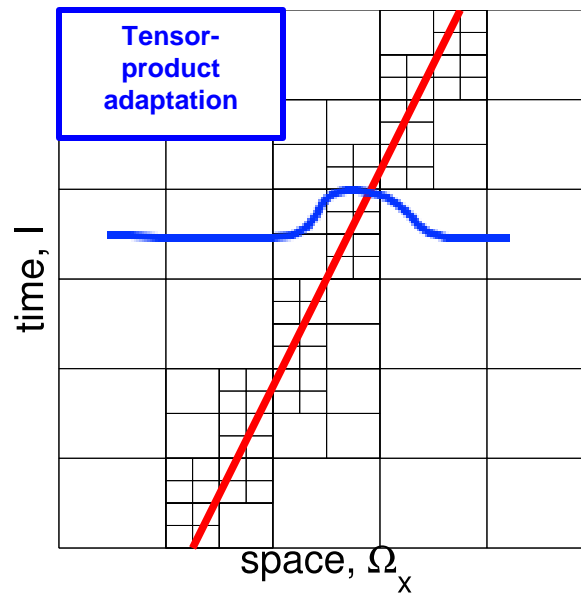
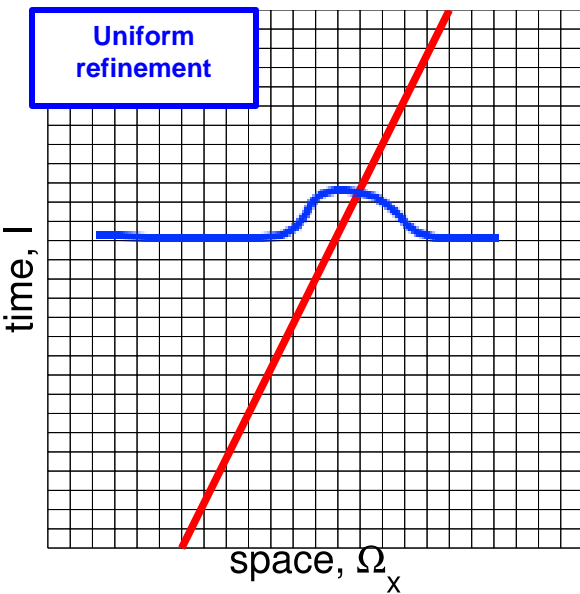
- MIT NRA completed (next 2 slides)



RANS-SA:  $M=0.15$ ,  $Re=6E6$ ,  $AOA = 10$  deg

- **FEM allows rigorous output error estimates and compact higher-order discretizations**
- **Recent study of RANS benchmark problems shows:**
  - Adaptation is critical to realize benefits of higher-order discretization
  - Optimal meshes depend on discretization order
  - 10x decrease in total CPU time compared to second-order finite volume (FUN3D)
- **Three-dimensional applications have demonstrated similar benefits however adaptive meshing for complex geometries remains a barrier**

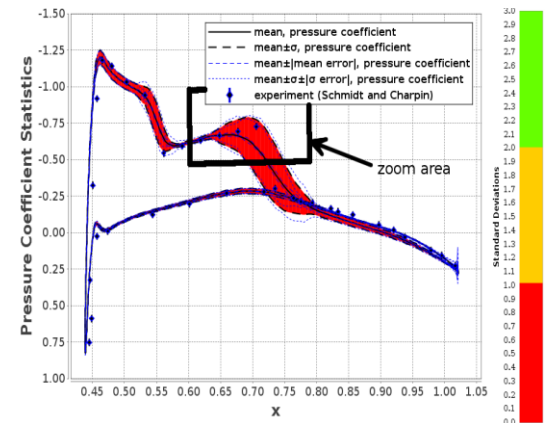




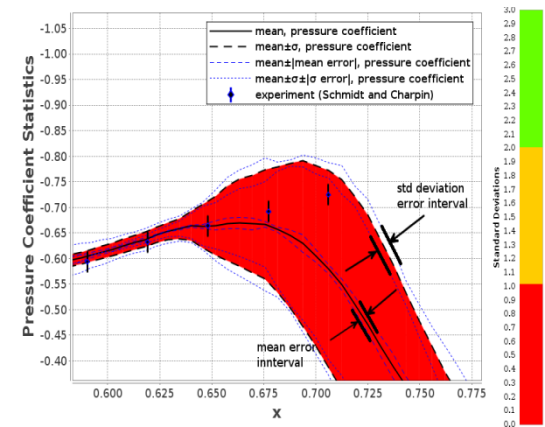
- Higher-order output-based adaptive space-time DGFEM
- Feasibility demonstration on 2D cylinder flow

# Combined Uncertainty and Error Bound Estimates for General CFD Computations

- **Excessive numerical errors can render computed uncertainty statistics misleading and meaningless**
  - Quantify impact of numerical errors on computed uncertainty to provide useful statistics to engineers
- **A unified framework for combined uncertainty and a-posteriori error bounds estimates:**
  - If simulation has no uncertainty, then standard a-posteriori error bound estimates are obtained
  - If simulation has no numerical error, then standard uncertainty estimates are obtained
  - If simulation has both uncertainty and numerical error, then uncertainty statistics with error bound estimates are obtained
- **Initial implementation/testing in NASA's CFD code, OVERFLOW**



ONERA M6 wing with uncertain inflow conditions. Surface pressure statistics at 65% span location.



Zoom close-up showing uncertainty error bound estimates for mean and standard deviation.

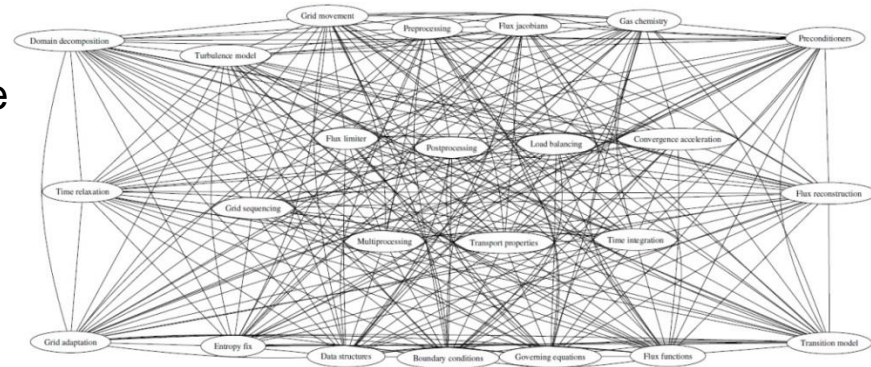
- **FUN3D is used for aircraft/spacecraft analysis and design**

- Aerodynamics, loads, noise, sonic boom, aeroelastics
- New RCA models incorporated/evaluated

- **Originally for algorithm development**

- **Increased size of team as code reached production-level capability**

- Code evolved without shared design principle
- Result is awkward dependencies that are difficult to navigate and maintain
- Difficult to collaborate with outside organizations for multidisciplinary developments



- **Refactor the code**

- Cleaning out unused, experimental, or poorly implemented code
- Framework with distributed control
- Isolate common components that are independent of discretization or physics
- Easy insertion of multiple discretization schemes and physics models
- Provide increased flexibility in coupling with other disciplines, partner with outside organizations



# Summary

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- **RCA: Foundational research that supports all NASA Missions**
- **RCA research aimed at advancing the state-of-the art of CFD**
  - Accuracy
  - Speed
  - Robustness/Reliability
- **CFD Validation Experiments A Critical Need**
- **Working towards Vision 2030, to enable**
  - Aircraft certification by analysis
  - Analysis/design of new aerospace vehicles without wind tunnel testing



